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QUARTERLY REPORT ON

Research in Electrohydrodynamics and
Wave-Type Magnetohydrodynamic A-C Power Generation

NASA Grant No. NsG-368

Covering the Period
1 February, 1964 to 30 April, 1964

Supervised by
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* Personnel involved in each project are listed directly below the project heading.

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QUARTERLY REPORT ON
Research in Electrodynamics and
Wave-Type Magnetohydrodynamic A-C Power Generation
NASA Grant No. NsG-368

This report summarizes research activities during the period 1 February, 1964 to 30 April, 1964 on NASA Research Grant NsG-368. As was done in the Semi-Annual Report dated 31 January, 1964, the work is divided into four main parts:

1. Traveling-wave MHD A-C power generation;
2. Alternating-current MHD conduction generators;
3. Continuum feedback control of EHD and MHD systems;
4. Basic investigations of EHD surface interactions.

The status of each project is as follows:

1. Traveling-Wave MHD A-C Power Generation

Personnel: H. H. Woodson, Professor
H. A. Haus, Professor
A. T. Lewis, Instructor (Ford Post-Doctoral Fellow)
G. L. Wilson, Teaching Assistant (Ph.D. Candidate)
M. M. Lind, Teaching Assistant (S.M. Candidate)
F. H. Chasen, S.B. Thesis Student

In the theoretical part of this study the one-dimensional, small-signal, linear, partial differential equations, including electrical losses in the plasma and tight coupling between circuit and plasma, have been written. From these equations, a sixth-order dispersion relation with complex coefficients has been obtained. A computer program for extracting the roots of the dispersion relation has been obtained. Computer results have been checked by manual calculations to verify that the program yields the correct roots. The roots of the dispersion relation are now being calculated for suitable ranges of system parameters. The boundary conditions have been derived and a computer program already exists for finding the gain of the system once the roots of the dispersion relation are known.

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The immediate plans are to continue with the process of determining the minimum size for a machine that will yield a useful power gain for each value of plasma parameters (magnetic Reynolds number) and each value of the coefficient of coupling.

In the Semi-Annual Report dated 31 January, 1964 it was reported that disturbances had been excited and detected and that the characteristics of those disturbances were consistent with the theoretically-expected behavior of magnetoacoustic waves. Further experimental investigation in the form of measurement of the perturbation magnetic field associated with the disturbance and measurement of the propagation velocity as a function of applied magnetic field indicated that the disturbances were acoustic. The fact that the velocities of the disturbances were considerably higher than the acoustic velocity indicates that the disturbances were actually acoustic shock waves. Further detailed studies of plasma properties verified this result.

The experiment is being modified in an attempt to establish an operating regime in which magnetoacoustic waves can be excited. The first step in this procedure is to use spectroscopic techniques and different construction materials to minimize contamination in the experiment. The primary objective is to produce a plasma whose composition is known. In connection with this work, members of our research group have had discussions with Messrs. William Grossman and Roger Stewart of NASA Langley Research Center who have been working with similar systems. An exchange of visits between our groups is planned in order to effect a better interchange of knowledge on problems of mutual interest.

After the contamination of the plasma is minimized, the plan is to proceed with excitation and detection of magnetoacoustic waves using a distributed, magnetic-field excitation and detection

circuit that will couple with magnetoacoustic resonances in the experimental system. In this modification the plasma properties, magnetic field strength, apparatus size, and operating frequency are much the same as those reported by Lindberg and Danielson.* Consequently, we expect to be able to study magnetoacoustic waves as they did except that our plasma will have a flow velocity in the direction of wave propagation, leading to the possibility of an amplifying interaction.

* Lindberg, L. and Danielson, L., "Magneto-Acoustic Oscillations in a Cylindrical Plasma Column," Physics of Fluids, vol. 6, no. 5, May 1963, pp. 736-744.

2. Alternating Current MHD Conduction Generators

Personnel: H. H. Woodson, Professor
G. L. Wilson, Teaching Assistant (Ph.D. Candidate)
H. Arndt, Research Assistant (S.M. Candidate)
W. Euerle, S.B. Thesis Student
J. Ravin, S.B. Thesis Student

Theoretical work in this area has proceeded along two lines. First, the cross-coupled generators, which were described in the two-phase version,^{*} are being studied in a general n-phase configuration. The object is to determine the factors which limit performance and thereby establish which number of phases yields the best performance with minimum field-conductor mass.

The second line of theoretical study has been directed toward determining the most advantageous use of the Hall-effect asymmetry in providing the gyrator action necessary for direct MHD a-c power generation without the necessity of tuning capacitors. Two major results have been obtained. First, if the working gas of the MHD generator is used to provide the Hall effect for gyrator action, the highest frequency of operation is obtained when a segmented-electrode generator is coupled conductively to a Hall generator section which is loaded with an inductor. Such a generator, which can operate at a higher frequency than can the cross-coupled, transverse-current generator, has been described in an Internal Memorandum.^{**} Second, if one considers a device, separate from the MHD generator, in which the Hall effect is used to supply

^{*}Woodson, H.H., "A-C Power Generation with MHD Conduction Machines," R.L.E. Q.P.R. No. 69, April 15, 1963, p. 93, M.I.T.

^{**}Arndt, H., "A-C Power Generation with Coupled Conduction and Hall Generator Sections," M.I.T., Dept. of Elec. Eng., Energy Conversion Group, Internal Memo. No. 91, March 12, 1964.

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reactive power, then considerably more freedom is allowed in choosing parameters. An analysis of such a device has been made^{*} and it has been shown that the performance is limited only by the mobility of the current-carrying charges. Suitably high mobilities can be obtained with a low pressure plasma and with certain semiconductors. This concept is being studied further with a view toward designing an experimental model for studying the performance characteristics.

The material described above will soon be prepared for presentation in a technical journal. Also, this material has been supplied to the M.I.T. Patent Office and it is contemplated that patent applications will be filed.

The recent work on the conduction generator experiment has been directed toward obtaining the longer test time that is needed for a-c generator experiments. The first step in this process has been to replace the LC channel excitation circuit with an artificial transmission line to make the driving current more nearly constant for the duration of the experiment. This modification has been successfully completed with a resulting increase of approximately a factor of two in the test time. It has also been found that operation of the experiment in this manner can significantly reduce the contamination for some conditions of operation. The experiment is being recalibrated to determine the plasma properties obtainable in order to determine whether or not it is possible to perform generator experiments. When this is completed, generator experiments will be performed or further modifications will be made.

^{*}Woodson, H.H., "A Hall-Effect Gyrotator for Supplying Reactive Power," M.I.T., Dept. of Elec. Eng., Energy Conversion Group, Internal Memo. No. 90, February 7, 1964.

3. Continuum Feedback Control of EHD and MHD Systems

Personnel: J. R. Melcher, Assistant Professor
M. V. Nannetti, Pan-American Fellow (S.M. Candidate)
J. M. Crowley, A.E.C. Fellow (Ph.D. Candidate)

Our program for the development of concepts and techniques concerned with the control of continuum electromechanical systems is about to achieve its first objective. We have endeavored to begin with experimentally realizable systems that are as simple as possible, with the intent of developing mathematical descriptions of simple systems, and at the same time, experimentally showing that the theoretically predicted behavior can, in fact, be realized. As our first objective, we have undertaken the stabilization of a one-dimensional, elastic continuum coupled to an electric field. This system is described in reference 1. The actual experiment consists of an elastic wire fixed at the ends and stressed by a transverse electric field. The theory of this system is developed in reference 1, which will be submitted for publication in the near future. In the past few weeks, an experiment has been tested which demonstrates the theoretical description of feedback stabilization for a two-station system. We have succeeded in producing electric pressures with feedback which are better than four times those possible without feedback. Theoretically, the improvement (for a two-station system) should never be greater than about 5.5. We have learned several important lessons from doing this experiment. All types of overstability observed in the past have not been due to the mechanism described in reference 1. Although the feedback loops used in the system are virtually without phase shift, the extremely small phase shift is enough to produce overstability in our very high "Q" electro-mechanical system with loop gains far below those necessary to significantly stabilize the electric-field-induced, static instability.

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Hence, in order to achieve essentially the postulated positional feedback, it has been found necessary to compensate the feedback loops with "lead" networks. It is hoped that in the next few weeks quantitative correlation of this experiment with the theory will be completed and presented in the form of a journal article.

With the completion of this stage of theoretical and experimental work, we are returning to the more complicated problem of stabilizing a Rayleigh-Taylor type fluid instability. Our present equipment and techniques will be applied to an experiment very much as described in the Semi-Annual Report of 31 January, 1964. Results of this more complicated experiment have been reported previously, and we feel that we are now in a position to further develop both the theory and the experiment. The theoretical work is presently under way, and includes a description of the EHD system and the similar MHD system. This problem represents a second stage in our theoretical and experimental program which we hope to complete late next fall. A third stage, involving a surface-coupled, magnetic system is presently in the planning stage.

In the Semi-Annual Report Dated 31 January, 1964, an experiment involving the control of an elastic plate in an electric field was described. This project will make use of the same apparatus as was used for the previously-described experiment. The project, which is the basis of a Master's thesis, is intended to extend the theoretical techniques which have been developed to a situation involving a different type of dispersion. The essential contribution of this work will be theoretical rather than experimental.

A type of instability common in convective systems (such as boundary layers and channel flows) is the convective instability. An EHD form of this instability has been studied extensively (see Section 4 of the Semi-Annual Report, 31 January, 1964) so that we

now have a good understanding of both our ability to characterize the physical system and the mechanism for exciting and detecting the instabilities. As the basis for a doctoral thesis, work is presently underway to develop concepts and techniques necessary to control the convective instability. We feel that the liquid EHD jet affords as simple a starting point for this work as is available.

4. Basic Investigations of EHD Surface Interactions

Personnel: J. R. Melcher, Assistant Professor
J. M. Crowley, A.E.C. Fellow (Ph.D. Candidate)
F. D. Ketterer, Instructor (Ph.D. Candidate)
E. B. Devitt, S.B. Thesis Student
K. L. Doty, S.B. Thesis Student
R. A. Grant, S.B. Thesis Student
E. Lombrozo, S.B. Thesis Student

Work is continuing in the first two areas mentioned in Section 4 of the Semi-Annual Report of 31 January, 1964. It is intended that a formal report will be available shortly concerning the basic investigation of single-stream, convective instabilities.

Careful stability measurements are currently underway for the polarization interaction (EH-1p) in a medium-frequency, electric field. The results for the one fluid tested so far support our suspicion that the theory for the polarization interaction with a d-c field can be extended to the medium-frequency, a-c interaction simply by substituting the rms value of the electric field for the d-c value. In connection with this experimental work, a complete numerical description of the conditions for impending instability is being developed for each of the fluids under test. The type I (perpendicular field) tests will be completed within the next few weeks in conjunction with a S.B. thesis. During the summer, a simple resonator apparatus will be constructed so that this work may be extended to type II interactions (parallel fields). We feel that these results will be a significant adjunct to work which is currently being carried on elsewhere in connection with heat transfer in electric fields, and hence it will be presented for publication late next fall.

Reference

1. Melcher, J.R., "Electrohydrodynamics of a Thin Conducting Film Stabilized by a Continuum of Feedback," M.I.T., Dept. of Elec. Eng., Energy Conversion Group, Internal Memo. No. 94, April 3, 1964. (To be submitted for publication in near future.)